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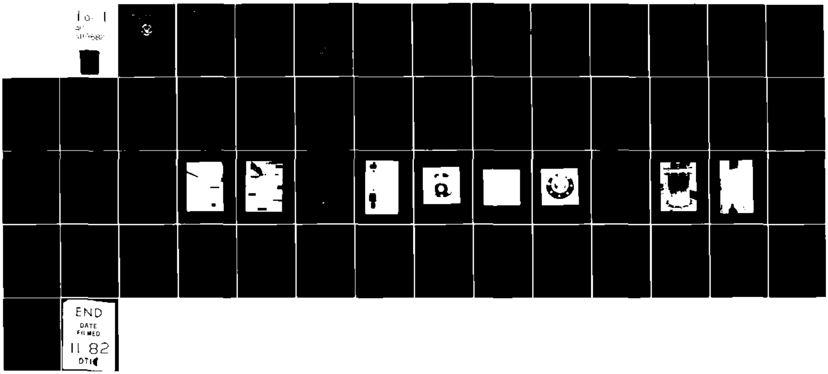

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

AN EXPERIMENTAL APPARATUS TO STUDY
ENHANCED CONDENSATION HEAT TRANSFER
OF STEAM ON HORIZONTAL TUBES

by

Raymond Lynn Krohn

June 1982

Thesis Advisor: P. J. Marto

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An Experimental Apparatus to Study Enhanced Condensation Heat Transfer of Steam on Horizontal Tubes

by

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Lieutenant Commander, United States Navy
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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

In an effort to explore the possibility of building compact naval steam condensers, an experimental apparatus was designed and constructed to study enhanced condensation heat transfer of steam on horizontal tubes. Special care was taken to ensure a leak-tight apparatus so that the non-condensable gas content of the steam can be kept to a few parts-per-million. The boiler and steam piping is made of glass and stainless steel with rubber gaskets. Copper is used for the condensing tubes. The completed system has been tested satisfactorily at full power.

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I. INTRODUCTION

A. SIGNIFICANCE

Surface condensers play an important role in marine propulsion and improved heat transfer in a steam condenser can reduce condenser size, and therefore cost, for a given heat load. Various meetings have addressed the needed research which must be performed in order to attain t s improvement in surface condenser performance [Ref. 1,2,3]

In recent years, there has been an increased awaren regarding the use of enhanced heat transfer surfaces in the design of heat exchangers [Ref. 2,4,5,6,7]. Webb [Ref. 8] in 1980 provided an excellent review of enhancement methods for particular use in condensers. In general, these methods may be divided into tube-side enhancement (on the cooling water side) and shell-side enhancement (on the steam side) techniques. Enhancement on the tube side has been reviewed by Bergles and Jensen [Ref. 9] in great detail. Shell-side enhancement has included surface coatings, low integral fins, fluted tubes and roped tubes.

The largest thermal resistance to heat flow in conventional surface condensers is usually on the water side, but a significant portion of the overall resistance exists on the shell side. As water-side enhancement occurs, the need to enhance on the shell side goes up. A variety of tubes have been proposed which allow enhancement on both sides at the same time. It has been found, however, that the preferred tube shape for one side of the tube is not necessarily best for the other side. It is important therefore to examine independently the best enhancement techniques on both sides.

During the past several years, a research effort has been underway at the Naval Postgraduate School to model steam surface condensers and analyze their thermal performance using numerical techniques [Ref. 10,11,12]. Numerous computer runs have been made to examine which combination of inside and outside enhancements gives the most dramatic improvement. With this preliminary information, it is felt that steam-side enhancement techniques should be further studied to determine the ultimate heat transfer improvement which can be reasonably expected on the steam side.

B. OBJECTIVE

The specific objective of this thesis was to design and construct an experimental apparatus that could accept tubes with several different surface enhancement techniques so as to be able to study enhanced condensation heat transfer processes on the outside of horizontal condenser tubes. Both filmwise and dropwise modes of condensation can be studied with the overall objective of establishing the most effective and reliable means of enhancement.

II. DESCRIPTION OF EXPERIMENTAL APPARATUS

A. OVERVIEW OF SYSTEM

Figure 1 is a schematic representation of the experimental apparatus. All major components were made of stainless steel or glass to avoid contamination problems, and to facilitate thorough cleaning. A suitable gasket material was chosen to minimize leakage and outgassing effects.

Steam generated in the boiler flows vertically downward over the test tube to an auxiliary condenser. Special care was taken to ensure a leak tight apparatus so that the non-condensing gas content of the steam can be kept to a few parts-per-million (ppm). A double glass window, heated by hot air to prevent fogging, is used in the test section so that the mode of condensation can be observed and photographs (both still and motion picture) of all important phenomena may be taken.

Figure 2 is a photograph of the experimental apparatus. The apparatus can be divided into eight major components: 1) the condenser test section, 2) the boiler, 3) the steam piping, 4) the dump condenser, 5) the auxiliary section and feed piping, 6) the support systems and 7) instrumentation.

B. CONDENSER TEST SECTION

The condenser test section is made of stainless steel six inches in diameter and 18-inches long. It is shown in the top of Figure 3. Flanges on the top and bottom provide for connection to the upper glass section and lower auxiliary section with eight 3/8-inch bolts and eight Belleville spring washers on each bolt. Belleville spring washers are used on all bolts to ensure tightness during thermal cycling of the complete system. Figure 4 shows a schematic of the details of the test section. The test tube is centered in the middle of the test section. The test tube has an active length of 5 1/2 inches and can have an outside diameter of up to 2 inches, with the ends 5/8-inch in diameter to fit the standard nylon holding rings. Figures 4 and 5 show details of the test tube and nylon holding rings. These nylon holding rings provide 3 O-ring seals for system tightness. Lips, that can be seen in Figures 5 and 6, are provided on the holding ring to prevent any condensate that might be on the wall from draining on the test tube. The test tube is insulated with a nylon washer at the inlet to the test tube and a nylon water passage on the outlet to prevent axial heat conduction from the test tube. The water inlet area shown in Figure 4 was

modified to include a nylon washer so that the water flow would be uninterrupted. Water from the test tube is dumped to the drain. A nylon mixing chamber, shown in Figures 7 and 8, was designed to mix the water leaving the test tube so that accurate average coolant temperatures could be measured. Water flows through a 3/8-inch center hole, then flows radially outward outward to a set of four holes. These four 1/4-inch diameter holes are on a 5/8-inch diameter hole circle. Water then flows inward and through a 3/8-inch center hole. A 4 1/2-inch diameter, double glass window heated by hot air to prevent fogging is provided for visual observation of the test section. This window can also provide access to the condenser tube when it is mounted in place. A 1/2-inch diameter stainless steel tube for pressure measurements is welded on an angle to the upper half of the test condenser to prevent condensate from collecting in the tube.

Three design considerations dictated the condenser test section size. Dropwise promoting coatings are limited to 6-inches in length due to the size of vacuum furnaces available for vacuum deposition of the enhancement coatings. Steam velocity must be greater than 3 ft/s under all conditions to sweep away noncondensable gases and prevent stag-

nating regions. Cost of the overall system limited the maximum size of the steam piping to 5-inches in diameter. In addition, the length of the test tube determines the temperature rise of the cooling water, which under some operating conditions, will be on the order of 1 degree Fahrenheit. (See Appendix C.) An error of one tenth of a degree in this temperature rise would give a 10% error in the heat flow calculation. To minimize the experimental error, the tube should be as long as possible. Boiler heat capacity, steam velocity and test tube diameter are all dependent upon one another. A six inch diameter test section was selected and the active length of tube was chosen to be 5 1/2 inches to ensure a uniform steam velocity across the test tube without interference from the test section wall and to increase the accuracy of the data.

C. BOILER

The boiler section was constructed using two pieces of Corning Pyrex glass and a stainless steel plate with immersion heaters.

1. Outside Envelope

Figure 9 shows the details of the bottom plate. The bottom is 16.75-inches in diameter and was constructed from

1/2-inch thick 304 stainless steel. The center was drilled and tapped to accept a standard 1-inch stainless steel Swagelok male connecter for the condensate return line to the boiler. Ten 23/32-inch diameter holes on a 8.46-inch diameter circle were drilled and tapped to accept the immersion heaters. For connection to the glass section, sixteen 1/2-inch diameter holes were drilled on a 15.5-inch diameter circle.

Two sections of Corning Pyrex glass make up the rest of the outside shell of the boiler. (See Figure 10.) The bottom glass section is 12-inches in diameter and 19.2-inches long. The next section of glass is a 12-inch to 6-inch reducer, 12-inches high. The maximum working pressure to prevent breakage recommended by Corning for the bottom glass section is 10.5 psig. All other glass components have higher pressure ratings, so 10.5 psig is the maximum pressure limit of the apparatus. All system components can operate under all vacuum conditions. Buna N rubber gaskets are used between all components. They have an allowable temperature range from -65 to 212 degrees Fahrenheit and a low outgassing rate. Cast iron flanges with an epoxy coating finish and inserts fit over the glass for connecting glass components to one another. Each

12-inch diameter connection uses twelve 3/8-inch diameter 3-inch long bolts with 8 Belleville spring washers on each bolt.

2. Immersion Heaters

Ten Watlow 4000-watt, 480-volt stainless steel sheathed heaters are used. Each heater is 5/8-inch in diameter and 11-inches long and has a 1/2- inch stainless steel threaded fitting for connection to the boiler base plate. All heaters are electrically connected in parallel. Heater selection and a six inch diameter test section insures that the steam velocity would be greater than 3 ft/sec. See Appendix B for steam velocity calculations.

D. STEAM PIPING

The 6-inch diameter Corning glass steam piping consists of 2 straight sections, 96-inches and 60-inches long, respectively and two 90-degree mitered ell fittings. The largest pipe is on top of the boiler, followed by the two ell fittings, and the 60-inch length of pipe just prior to the condenser test section (See Figure 2.) . All connections use cast iron flanges with an epoxy coating finish and inserts. Eight 3/8-inch bolts 3-inches long and 8 Belleville spring washers on each bolt are used to hold the

flanges together. The maximum working pressure recommended by Corning for 6-inch glass pipe is 15 psig.

E. DUMP CONDENSER

The stainless steel dump condenser is 6-inches in diameter and 18-inches long and provides for condensing all excess steam. Two helically wound coils of 3/8-inch copper tubing, one 5 1/2-inches in diameter and the other 4-inches in diameter, both 18-inches long, are silver brased to the bottom plate of the dump condenser. The dump condenser is flanged for connection with the upper auxiliary section and the bottom plate. Eight 3/8-inch bolts with 8 Belleville spring washers on each bolt are used to hold the flanges together. The bottom plate was drilled and tapped to accept a 1-inch male Swagelok connector for the condensate return line. A 1/2-inch diameter stainless steel tube near the bottom of the dump condenser is provided for noncondensable gas removal. This connection is on an angle to limit the amount of condensate removed from the apparatus during vacuum operations. A 1/2-inch diameter connection is provided for relief valve protection and a make up feed connection.

F. AUXILIARY SECTION AND FEED PIPING

The stainless steel auxiliary section is 6-inches in diameter and 10- inches long. Flanges are provided to connect the auxiliary section to the condenser test section and the dump condenser. The auxiliary section provides a four inch diameter connection for vacuum testing and provides a space to install a condensate collection device under the test tube for future studies.

The feed piping is 1-inch stainless steel piping connected from the dump condenser to the boiler using Swagelok fittings with teflon ferrules. A one inch Swagelok nut can be removed from the feed piping for draining the system.

G. SUPPORT SYSTEMS

1. Cooling Water System

Cooling water is supplied on a once-through basis using a tap water fitting. To avoid flow variations, the design is to have a constant supply head tank. Tap water flows into the tank and an overflow keeps a constant height of water. Water is pumped out of the tank through a flow-meter, into a straightening section, and then through the test tube. See Figure 1 for a schematic of the system.

Care was taken to ensure the water flow is uninterrupted before reaching the test section so as to keep coolant-side resistance the same from one test tube to the next.

Tap water is supplied directly to the dump condenser and then to the drain. Both cooling coils are supplied in parallel from a single water source.

2. Vacuum System

Two operational vacuum systems can be used for maintaining system vacuum. The first is a mechanical vacuum pump with a nitrogen cold trap to prevent moisture carryover into the pump. The second is an air ejector supplied by 180 psig air. Both systems will maintain vacuum at any desired pressure level greater than about 2 psia. If pressures of less than 2 psia are desired, then the vacuum pump with cold trap must be used.

B. INSTRUMENTATION

1. Heater Power Control and Instruments

The heater power controller is an existing Halmar model PA-1-2490 phase/amp single phase silicon controlled rectifier power amplifier designed to control and regulate a-c power. The maximum voltage out is 440 volts and the maximum current is 90 amps.

Meters of 0-300 volts and 0-300 amps were used for heater power indication. A voltage divider consisting of precision wire wound resistors was used to extend the range of the voltmeter. Actual voltage is 2.2 times the indicated voltage. Table 1 gives voltmeter calibration data.

2. Temperature Measurement Systems

Temperature is measured at the inlet and the outlet of the cooling water flow to the test tube. Condensate return temperature is also measured. An initial test tube has been built with six wall thermocouples 60 degrees apart. This test tube can be oriented so as to give temperatures at 12 angular locations arround the tube. A Hewlett-Packard 3054 computer driven data acquisition system using a HP 9826A computer driving a HP 3497 intelligent controller scanner voltmeter system was used for measuring temperature. This system was choosen for its high accuracy and easy data acquisition in futher tests. Accuracy of the system is 0.01% of the actual reading.

3. Pressure Measurement

Measurement of pressure inside the condenser test section was accomplished by using a U-tube mercury manometer which was marked off in tenths of an inch. This manometer was connected just above the actual test tube as shown in Figure 3.

III. ASSEMBLY OF SYSTEM

A thorough cleaning of all equipment is necessary to avoid contamination problems. Sparkleen, a laboratory detergent made for cleaning glassware, was dissolved in hot water and used to clean all apparatus parts. The parts were then rinsed with soft water. To prevent contamination, all sections were handled with latex gloves.

A. ASSEMBLY AND VACUUM TESTING

The boiler section was assembled after cleaning and both ends blank flanged. All bolts were tightened to the maximum recommended torque of 5 ft-lbs during assembly and after initial heatup of the complete system. The boiler section was vacuum tested to $4x10^{-6}$ torr. Each section was then added, piece by piece,and all bolts were tightened to the maximum torque, and then vacuum tested. The complete system was vacuum tested using the connection in the auxiliary section. The best vacuum obtained for the complete system was $5x10^{-5}$ torr using an NRC Special 4-inch Vacuum Pumping System. A vacuum of 27 inches of mercury was kept on the isolated system for 8 days without any noted increase in pressure.

IV. SYSTEM STARTUP AND TESTING

A. FULL POWER OPERATION AT ATMOSPHERIC PRESSURE

The boiler was filled with distilled water to a level six inches above the top of the heaters. Cooling water was started through only the dump condenser cooling coils with the dump condenser open to the atmosphere. Power was turned on and warmup of the boiler water was conducted at less than 200 volts to avoid excessive vibrations of the glass piping caused by nucleate boiling. At high input power levels to the boiler and at low temperatures of the boiler water, violent nucleate boiling occurred and caused severe vibrations of the boiler and glass piping. When the water began to boil, the input voltage was controlled to avoid over-pressurizing the apparatus while the noncondensable gases were forced out of the system from the dump condenser. The system was run at full power with only cooling water to the dump condenser. The maximum power obtained was 35 kw and the maximum steam velocity was 4.67 ft/s. Maximum power was limited by the heater input power controller.

B. FULL POWER OPERATION AT A VACUUM

The boiler was filled with distilled water to a level six inches above the top of the heaters. Cooling water was started through both the condenser test section and the dump condenser. A vacuum of 1.94 psia was held constant on the system by throttling a valve to an air ejector. Under a vacuum, more violent boiling action occurred. During heatup of the boiler, vibrations of the boiler and glass piping occurred at a lower input power level than the same condition except at atmospheric pressure. The maximum power obtained was 35 kw and the maximum steam velocity was 29.5 ft/s.

Maximum power can be obtained under all desirable conditions. During all operations, pressure in the apparatus never exceeded 1 psig. The minimum design steam velocity was obtained under all operating conditions. Condensation can be viewed under all situations through the double glass heated window. Figure 10 shows a picture of boiling at 100% power at a pressure of 1.94 psia. Figure 11 shows a picture of condensation at 100% power under a vacuum.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. An experimental apparatus has been designed, constructed and tested that allows studying enhanced condensation heat transfer of steam on horizontal tubes.

2. The minimum steam velocity of 3 ft/s has been exceeded under all maximum boiler operating conditions.

3. System tightness has been proven and the system stays tight after thermal cycling of the apparatus.

B. RECOMMENDATIONS

1. Hook up the 1 psig relief valve and a permanent make up feed line.

2. Hook up the permanent test tube cooling water system.

3. Calibrate and install all thermocouples.

4. Test the manufactured copper test tube with six wall thermocouples.

5. Carry out the study of enhanced test tubes.

APPENDIX A

TABLES AND FIGURES

TABLE I

Heater Voltmeter Calibration

Scale Reading	True RMS Volts
50	111
60	134
70	156
80	177
90	198
100	218
110	245
120	268
130	292
140	315

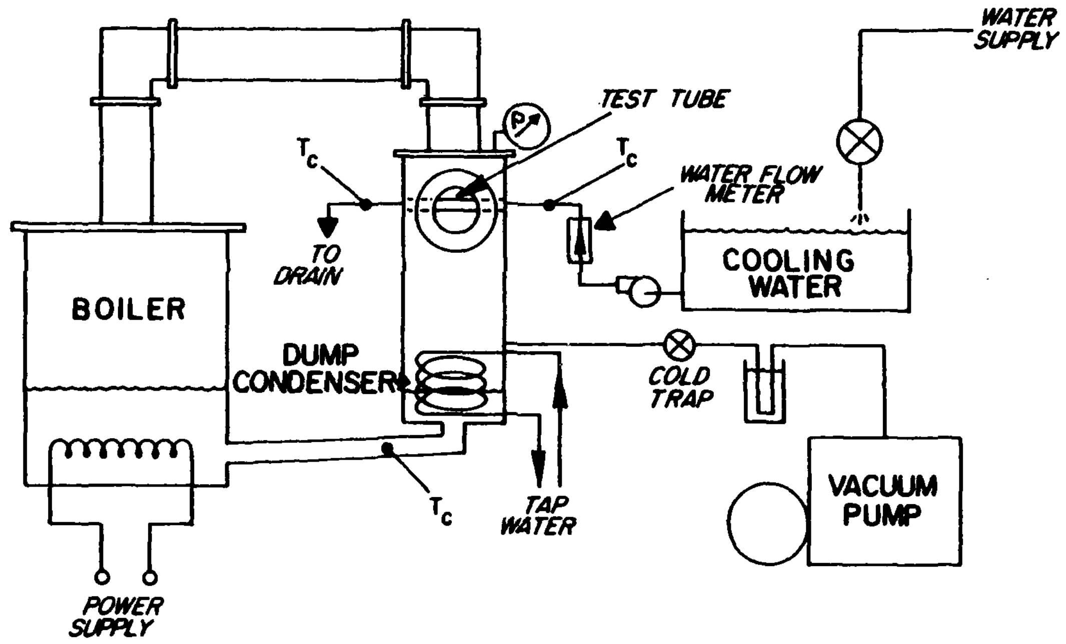

Figure 1. Schematic Diagram of Test Equipment

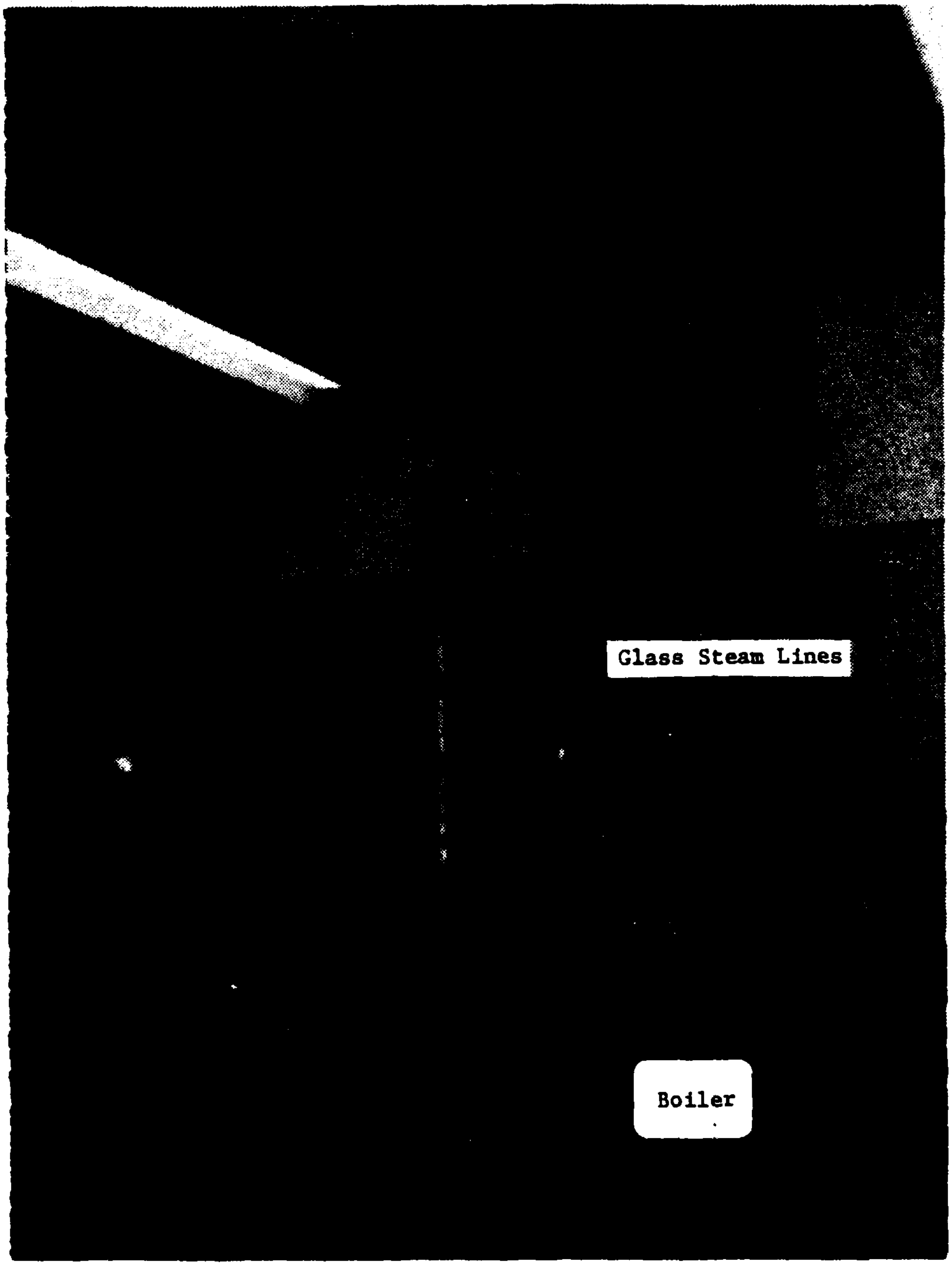

Figure 2. Photograph of the Experimental Apparatus

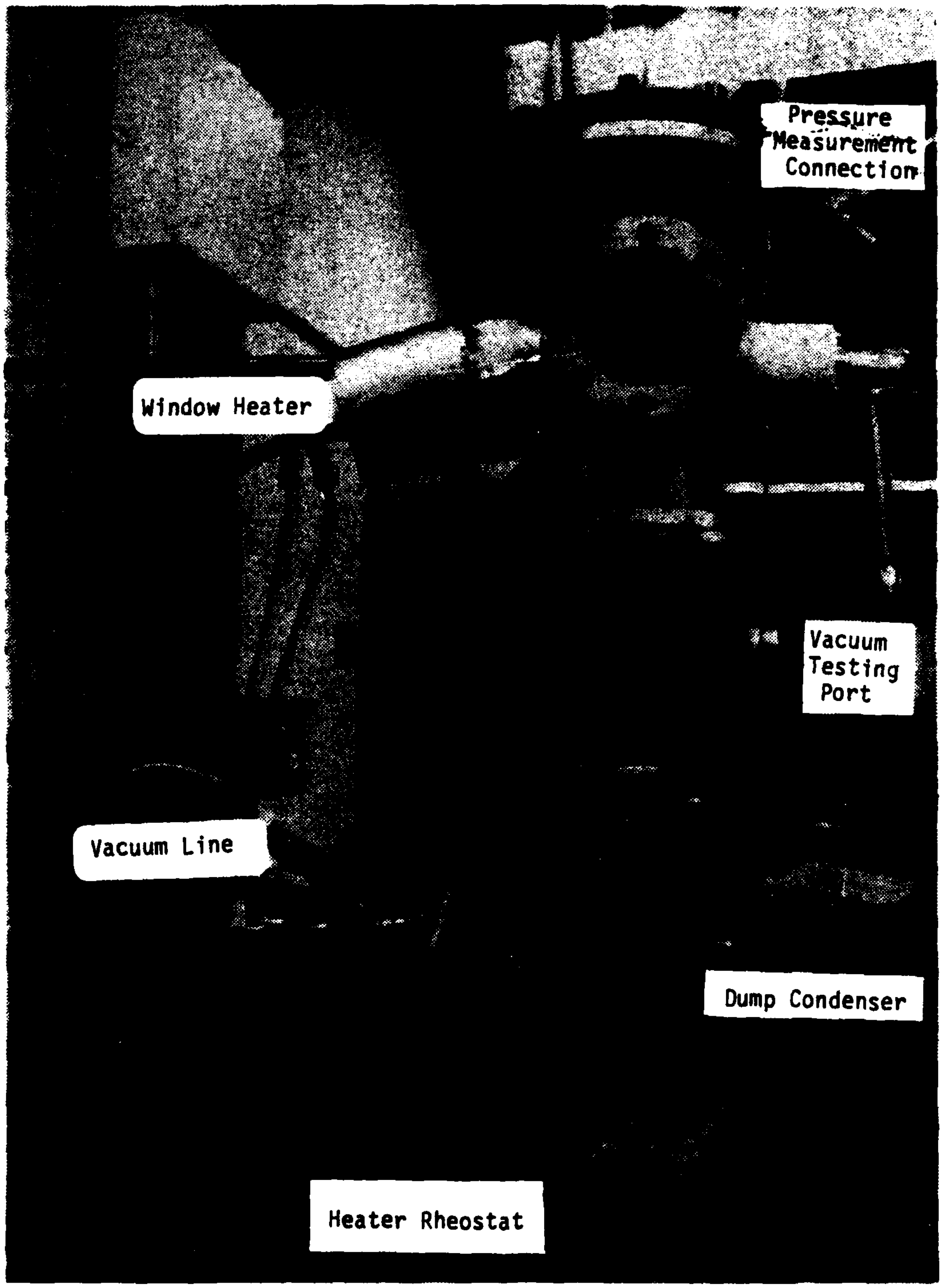

Figure 3. Photograph of Stainless Steel Components

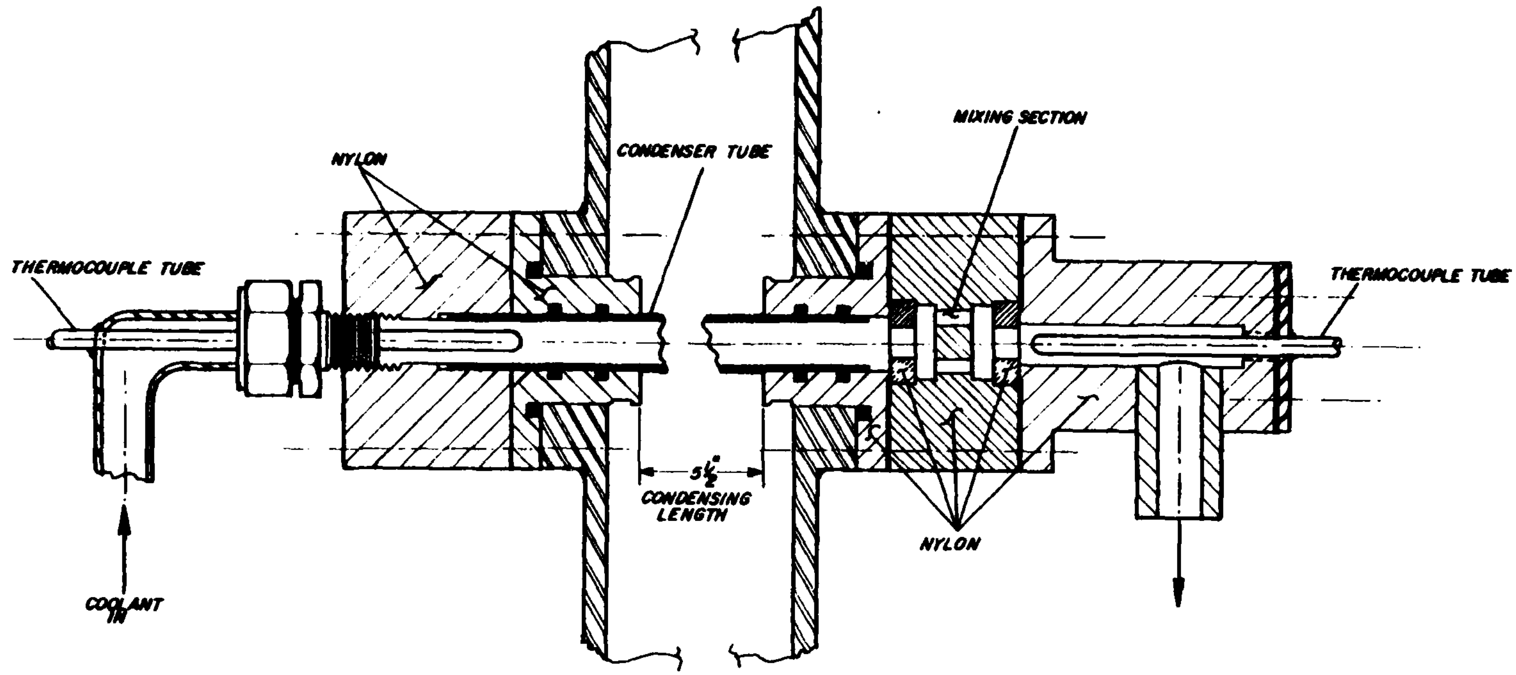

Figure 4. Schematic Details of the Test Section

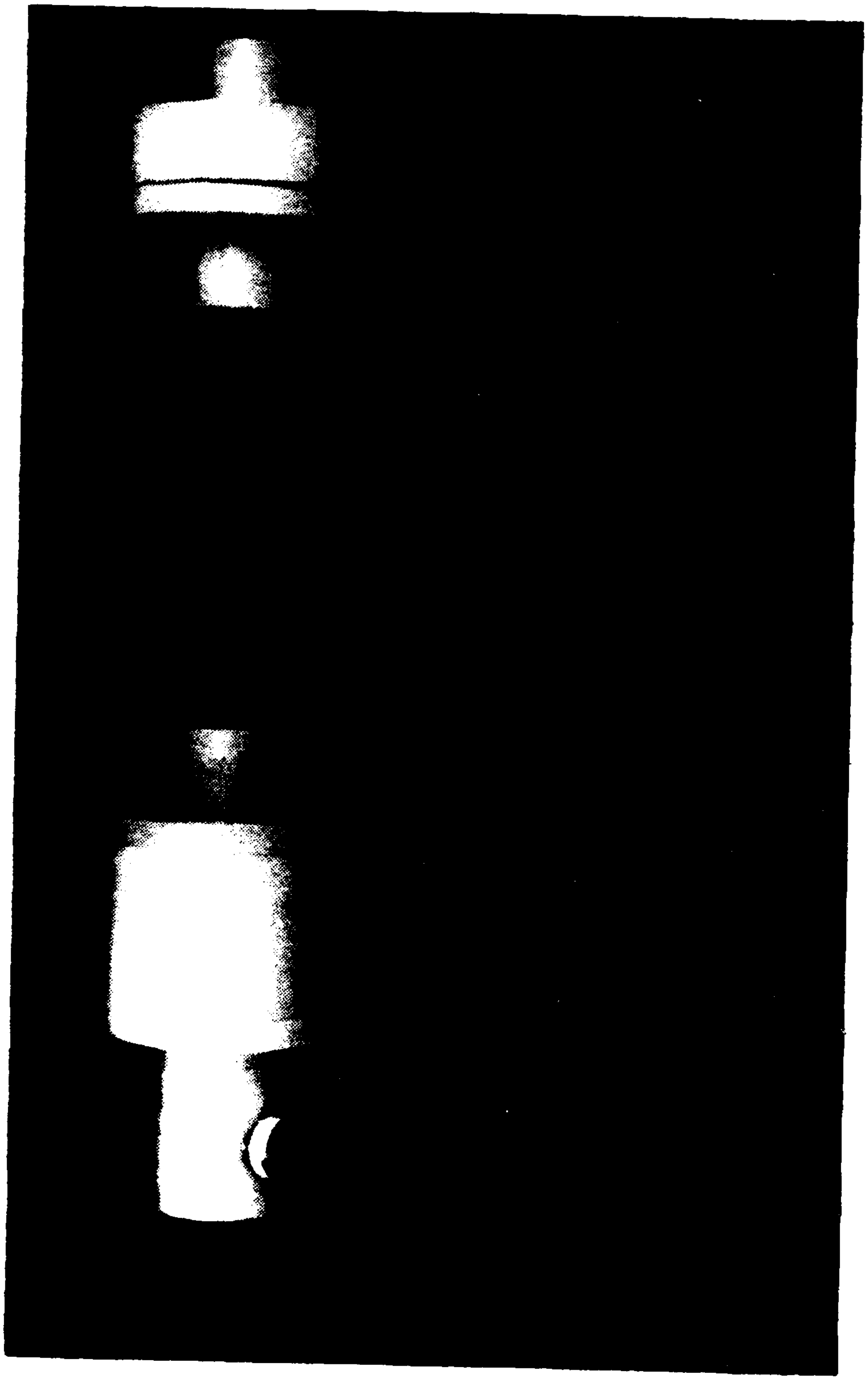

Figure 5. Photograph of the Test Tube and Nylon Pieces

Figure 6. Photograph of the Test Tube Nylon Holders

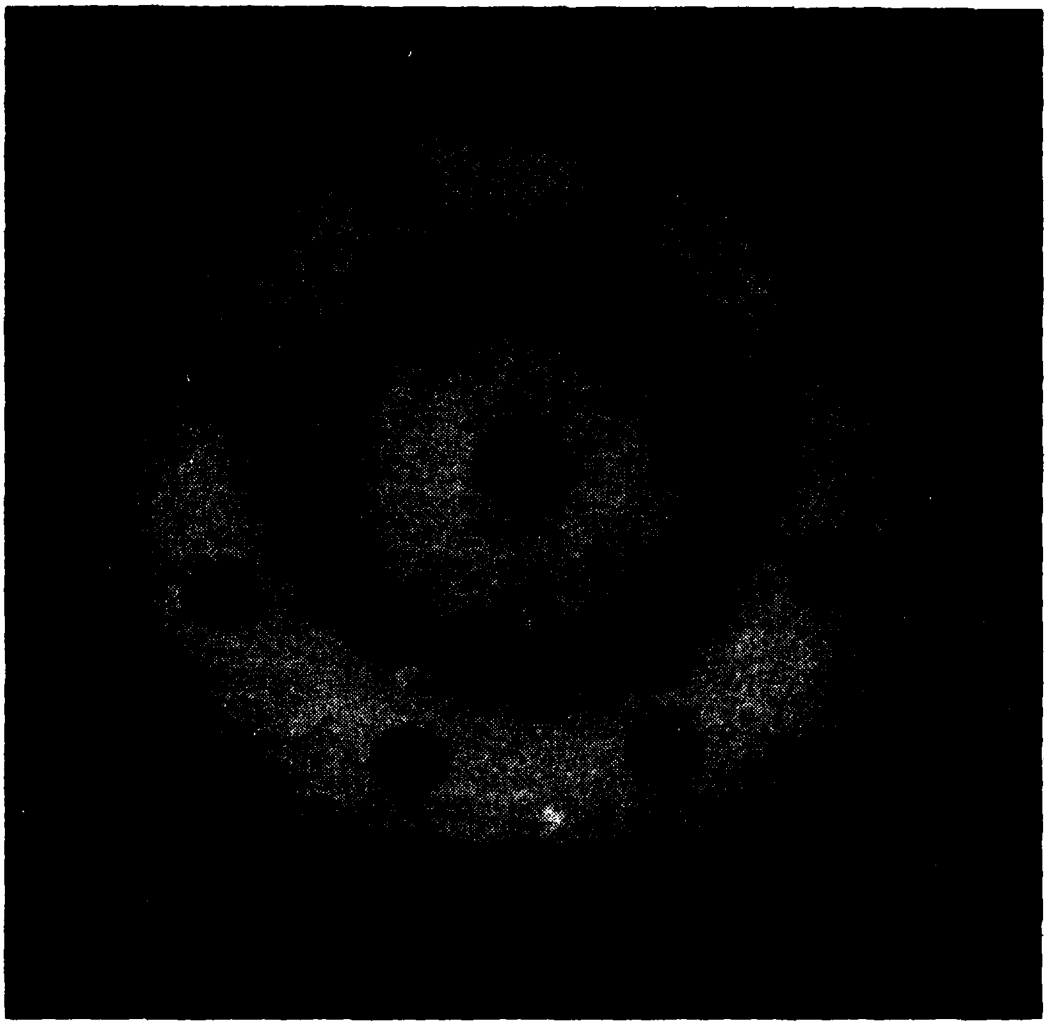

Figure 7. Photograph of the Water Mixing Chamber

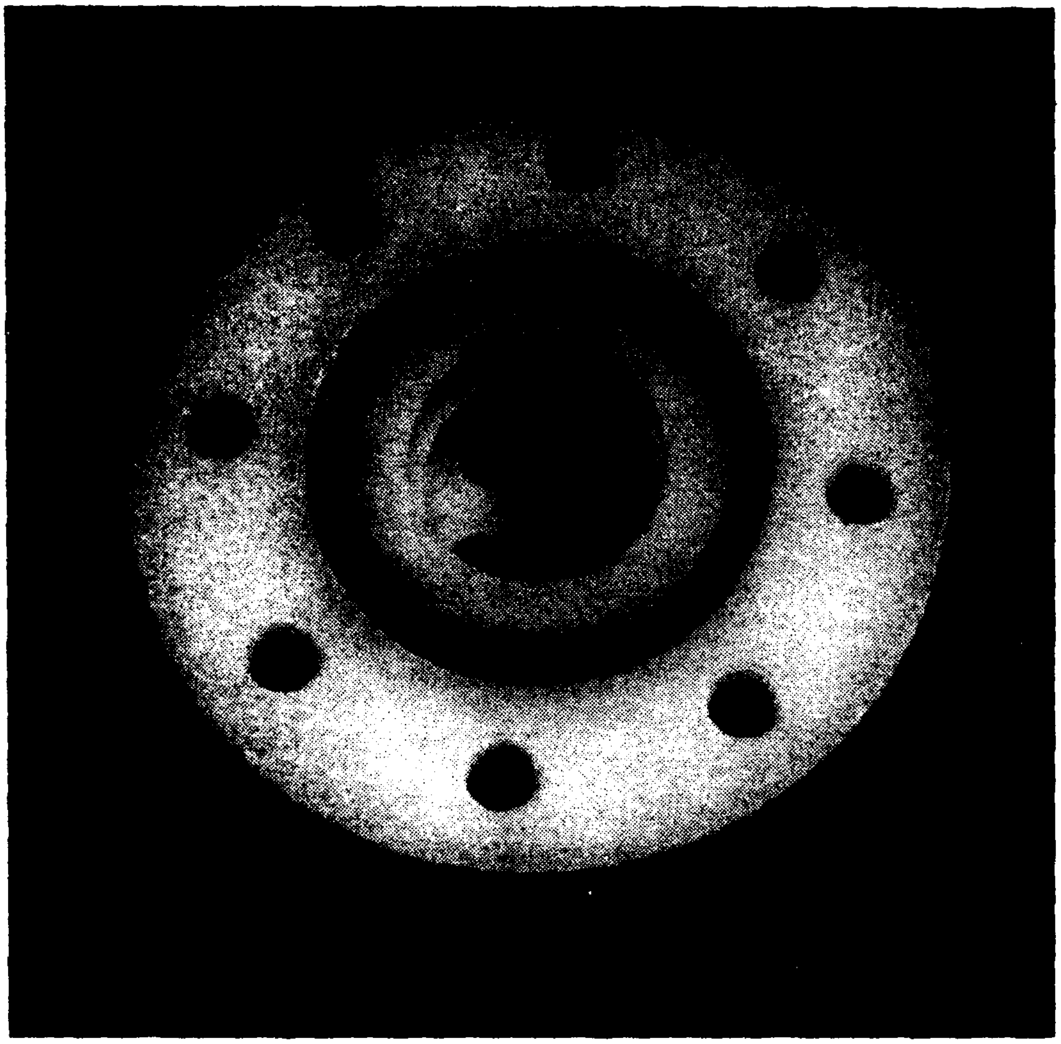

Figure 8. Photograph of the Disassembled Water Mixing Chamber

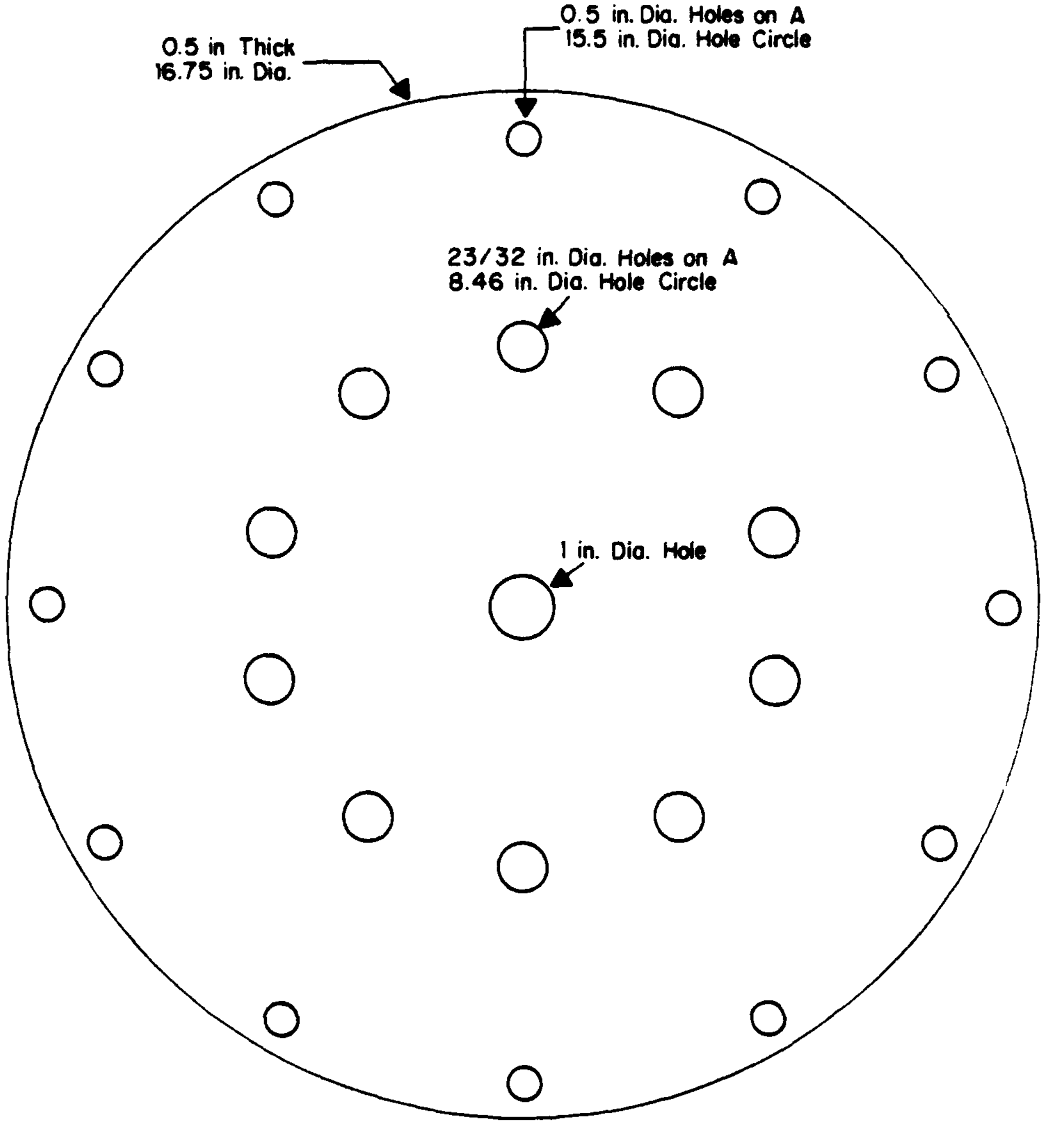

Figure 9. Details of Boiler Bottom Plate

Figure 10. Photograph of the Boiler in Operation

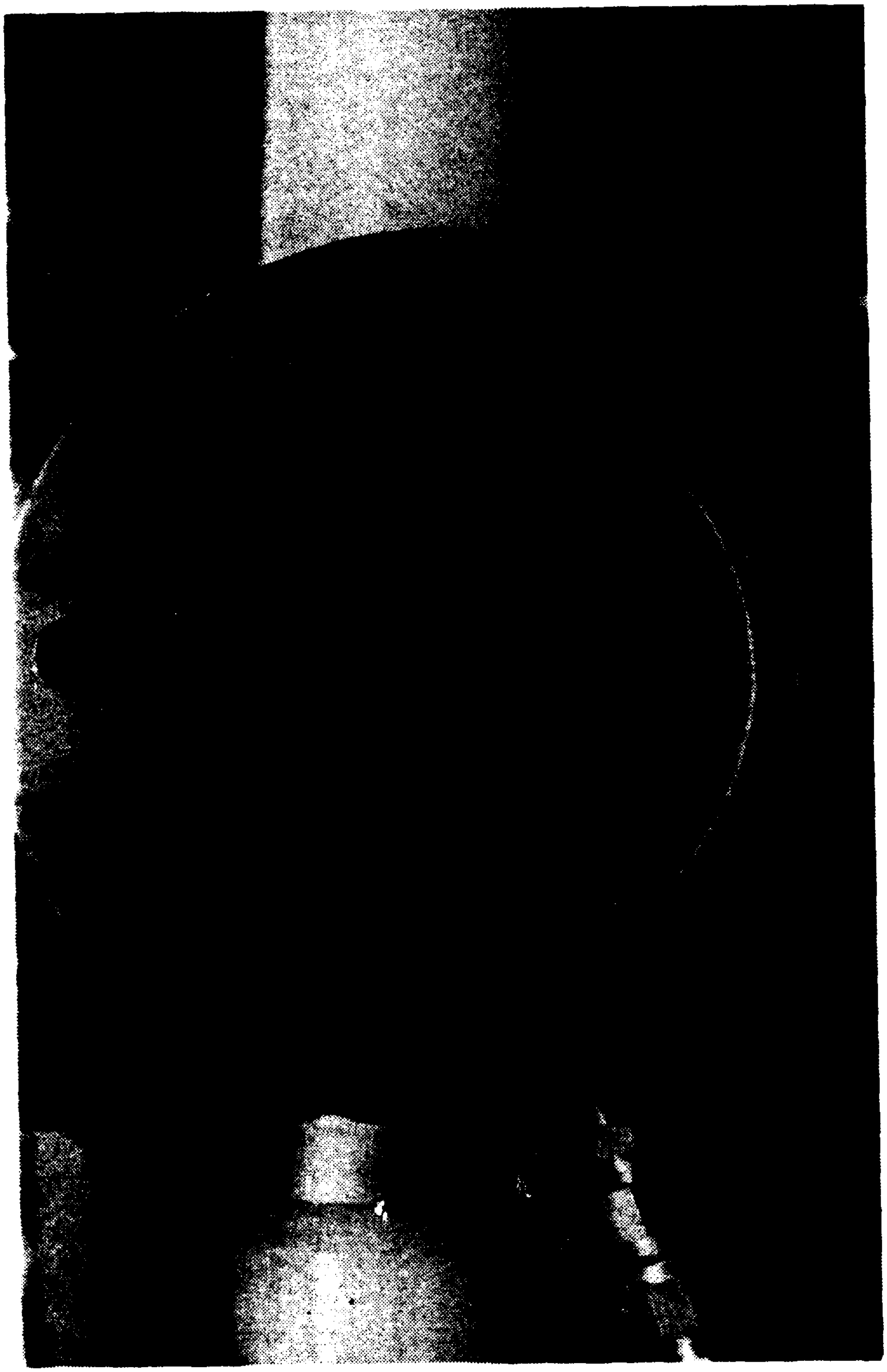

Figure 11. Photograph of Condensation on the Test Tube

APPENDIX B

CALCULATION OF THE STEAM VELOCITY

The following analysis was made to determine the steam velocities at atmospheric pressure and 1.94 psia.

Let Q=Heat transfer rate (Btu/hr)

A=Cross sectional area of steam piping (ft^2)

d=Diameter of steam piping (ft)

h_{fg}=Latent heat of vaporization (Btu/lbm)

ρ=Density of steam (lbm/ft^3)

V=Velocity of steam in steam pipe (ft/s)

$$Q = h_{fg}\ \rho\ A\ V$$

$$V = Q\ /\rho\ A\ h_{fg}$$

Under all conditions considered, d=0.5 ft

therefore A=0.196 ft^2

At atmospheric conditions and full power

$Q=35kw=119{,}525$ Btu/hr

$\rho=0.03731$ lbm/ft^3

$h_{fg}=970.3$ Btu/lbm , and

$V=4.67$ ft/s

At 1.94 psia and full power

$\rho = 0.00560$ lbm/ft^3

$h_{fg} = 1022.7$ Btu/lbm , and

$V = 29.5$ ft/s

APPENDIX C

CALCULATION OF COOLING WATER TEMPERATURE INCREASE

A set of calculations was performed to find the temperature rise of the cooling water for two operating conditions.

A=Cross sectional flow area of the tube (ft^2)

A_i =Inside surface area of the test tube (ft^2)

A_o =Outside surface area of the test tube (ft^2)

C=Specific heat (Btu/lbm °F)

D_i =Inside diameter of the test tube (ft)

D_o =Outside diameter of the test tube (ft)

h_i =Inside convection heat transfer coefficient (Btu/h ft^2 °F)

h_{fg}=Latent heat of vaporization

h_o =Outside condensation heat transfer coefficient (Btu/h ft^2 °F)

k=Thermal conductivity (Btu/h ft °F)

L=Length of the test tube (ft)

LMTD=Log mean temperature difference (°F)

$\dot{m}$=Mass flow rate (lbm/h)

Nu=Nusselt number

Pr=Prandtl number

q=Heat flow (Btu/h)

R_w=Thermal resistance of the wall (h °F/Btu)

Re=Reynolds number

T_i =Inlet water temperature (°F)

T_o =Outlet water temperature (°F)

U_i =Inside area overall heat-transfer coefficient (Btu/hr ft² °F)

U_o =Outside area overall heat-transfer coefficient (Btu/hr ft² °F)

T_s =Steam temperature (°F)

T_{sat} =Saturation temperature (°F)

V=Velocity (ft/s)

μ=Dynamic viscosity (lbf s/ft²)

ρ=Density of the fluid (lbm/ft³)

ρ_v=Density of the vapor (lbm/ft³)

The following are calculations of the water side parameters assuming an inlet temperature of 60°F. The inside and outside diameters, and the length are fixed.

D_i =0.0439 ft

D_o =0.0521 ft

L=0.458 ft

The properties of water for a temperature of 60°F are given below.

μ=2.731X10^{-5} lbf s/ft²

$\rho = 62.4$ lbm/ft^3

$Pr = 9.28$

$k = 0.3391$ Btu/hr ft °F

$C = 1$ Btu/lbm °F

Assuming a turbulent flow Reynolds number of 40,000, which is near that in operating condensers, water velocity can be obtained.

$Re = D_i \; V \rho / \mu$

$V = Re \, \mu / \rho D_i$

$V = 12.84$ ft/s

The Nusselt number can be obtained from an equation by Stylianou [Ref. 13] as follows:

$Nu = 0.03 \; Re^{0.8} \; Pr^{1/3}$

$Nu = 302.9$

The inside convection heat transfer coefficient can be obtained from the Nusselt number.

$h_i = Nu \; k \; / \; d$

$h_i = 2338.7$ Btu/h ft^2 °F

Wall resistance was calculated from the following:

$k = 223$ Btu/h ft °F (for copper)

$R_w = \ln \left(D_o / D_i \right) \; / \; 2 \pi \; k \; L$

$R_w = 2.656 \times 10^{-4}$ h °F / Btu

The following is a calculation of steam side parameters at atmopheric pressure. The properties of steam are given.

ρ=59.8 lbm/ft^3

ρ_v=0.037315 lbm/ft^3

h_{fg}=970.3 Btu/lbm

k_f =0.363 Btu/h ft °F

μ =8.89X10^{-6} lbf s /ft^2

Using the following equation for film condensation on horizontal tubes by Nusselt,

$$h_o=0.725\left[\rho(\rho-\rho_v)\ g\ h_{fg}\,k_f^3\ /\ \mu\, D_o\,(T_s-T_w)\right]^{1/4}$$

the outside condensation heat transfer coefficient was obtained.

h_o=4333.2/$(T_s-T_w)^{1/4}$

Assuming T_w=126°F, then h_o is obtained.

h_o=1422.9 Btu/h ft^2 °F

The overall heat transfer coefficient times the area is given as

$1/U_o A_o = 1/h_o A_o + 1/h_i A_i + R_w$

and $U_o A_o$ is calculated.

$U_o A_o$=61.759 Btu/h °F

Given a T_i =60°F and a T_{sat} =212°F, the LMTD can be expressed.

$$LMTD=(T_o-60^\circ)/\ln(152^\circ/(212^\circ-T_o))$$

The following two equations are solved for T_o.

$$q=U_o A_o \text{ LMTD}$$

$$q=\dot{m}\, C\, (T_o-T_i)$$

$$T_o=62.13^\circ F$$

The temperature rise of the cooling water is 2.13°F.

The following is a calculation of the steam side parameters at 2 psia. The properties of steam are given.

$$\rho=61.62 \text{ lbm/ft}^3$$

$$\rho_v=0.005659 \text{ lbm/ft}^3$$

$$h_{fg}=1022.5 \text{ Btu/lbm}$$

$$k_f=0.363 \text{ Btu/h ft }^\circ F$$

$$\mu=1.42X10^{-5} \text{ lbf s/ft}^2$$

$$T_{sat}=125.4^\circ F$$

The outside condensation heat transfer was obtained in the same manner as above.

$$h_o=3974.8\ /(T_s-T_w)^{1/4}$$

Assuming $T_w=90^\circ F$, h_o is calculated.

$$h_o=1629.5 \text{ Btu /h ft}^2\ {}^\circ F$$

The overall heat transfer coefficient times the area is calculated as

$U_o A_o$=66.65 Btu /h °F

and then the LMTD is expressed as

LMTD= $(T_o-60°)/\ln(65.4°/(125.4°-T_o))$.

Solve $q=U_o A_o$ LMTD=m C (T_o-T_i) for T_o

T_o =60.98°F

The temperature rise of the cooling water is 0.98°F.

A refinement in each of the above calculations would be to recalculate the assumed outside wall temperature T_w knowing $U_o A_o$, $h_o A_o$, and LMTD and to iterate the solution if the recalculated T_w is substantially different from the assumed value.

APPENDIX D

SAFETY CONSIDERATIONS AND GENERAL OPERATING PROCEDURES

A. SAFETY CONSIDERATIONS

1. Maximum pressure is 10.5 psig, limited by the boiler's maximum pressure.

2. Maximum power is 35 kw, limited by the controller output power.

3. Boiler heaters must remain covered with water when energized.

4. Do not exceed 200 volts on warmup of the boiler.

5. During system tightness tests, a rigid object must be placed between the apparatus and the vacuum pumping station to prevent breaking of the glass steam piping. A flexable pipe connects the vacuum pumping station to the apparatus and when the pressure is decreased a force is developed on the glass piping.

6. The air supply valve must be open whenever the heated window heaters are energized.

7. Belleville spring washers should be on all steam and boiler connections and arranged in accordance with the Corning installation manual.

8. Emergency shutdown of the boiler heaters can be done with one of two electrical breakers. One is located on the end of the panel that holds the heater controller and the other is located outside the south wall of room 106 in the large electrical breaker panel. Know the location of these breakers prior to running the apparatus.

B. GENERAL OPERATING PROCEDURES

1. Water can be transferred from the distilled water storage tank by hose to the boiler any time a vacuum is on the boiler.

2. Secure both boiler heater power supply breakers when the system is not in use.

3. Allow warmup and cooldown of the heated test section window of about 1/2 hour.

APPENDIX E

GENERAL STARTUP PROCEDURE

1. Fill boiler with distilled water to a level six inches above the top of the heaters.

2. For atmospheric pressure operation, open the vent.

2a. For vacuum operation with the air ejector, start the air compressor to charge the air flasks to 180 psig. Open the air supply to the air ejector. Open the air ejector suction line valve to the experimental apparatus. Throttle the suction line supply valve to maintain the desired vacuum.

3. Open the valve for the air supply to the condenser section window about 1/4 of a turn. Energize the heater for the air by turning the heater rheostat to 30. Adjust rheostat to heep the viewing window hot enough so no condensation occurs on the inside window.

4. Start water flowing to the dump condenser and the test tube.

5. Shut the two supply breakers for the boiler heaters.

6. Increase the voltage on the boiler heaters to a maximum of 200 volts during warmup. If the operating pres-

sure is very low, use a lower voltage for warming up the system to limit violent boiling action that causes vibration of the glass piping.

7. As steam starts to form when operating at atmospheric pressure, air is expelled from the apparatus and voltage to the heaters should be controlled to prevent exceeding 1 psig in the apparatus.

8. Once steam reaches the condenser test tube (about 30 min.), full power operation may begin.

APPENDIX F

GENERAL SHUTDOWN PROCEDURE

1. Decrease voltage to the boiler heaters to zero, then open both electrical supply breakers.

2. Adjust the rheostat for the heater of the condenser window air to zero.

3. Secure water to the dump condenser and test tube.

4. If in use, shut the air ejector suction valve, shut the air supply valve to the air ejector, and secure the air compressor.

5. If desired, unscrew the Swagelok nut in the feed line to drain the system.

6. About 1/2 hour after performing step 2 above, secure the air to the condenser window.

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